CHEMICAL ENGINEERING TRANSACTIONS

VOL. 103, 2023

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Panos Seferlis, Yee Van Fan, Athanasios Papadopoulos

ISBN 979-12-81206-02-1; **ISSN** 2283-9216

DOI: 10.3303/CET23103033

Application of Magnetic Phase Transition for a Novel Wireless Sensor Device for Body Temperature

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The recent several years of the global pandemic have brought attention to a societal need for large-scale monitoring and managing of human information concerning public health. One prominent way in which this is accomplished is by installing body temperature sensors, usually thermographic cameras, at the entrance of locations with a great number of people are expected to enter and exit. However, there are concerns with such a method regarding not only the accuracy and precision of the data but also the energy usage. The authors have proposed a novel body temperature sensor device that can potentially become a solution to the aforementioned concerns with the application of magnetic phase transitions. The proposed device utilizes the temperature-dependent magnetization properties and Faraday's law of electromagnetic induction to measure temperature in the form of electromotive force. Here, an elementary investigation of the magnetic properties surrounding temperature change is done using gadolinium to assess the potential of the proposed body temperature device. The results demonstrate that there is a material-specific temperature range in which there is a clear linear relationship between temperature and magnetization change, suggesting that this region indeed has the potential for operation as a novel temperature sensor.

1. Introduction

Throughout the recent few years of the global pandemic, and to a similar extent today where the situation has gotten significantly better, monitoring and managing human movement and condition have been a few of the core countermeasures for the prevention of outbursts (Chang et al., 2020). In doing so, one of the key methods in which infection cases are monitored is through monitoring body temperatures in many places, as body temperature is not only feasibly measurable but also a typical and significant indicator of health status. While there are several ways in which body temperature has been monitored on a large scale, two of the common methods are thermal imaging cameras, or thermographic cameras, and individual self-reporting. However, these methods have points of concern that raises the need for a novel body temperature monitoring method (Chang et al., 2020). The issue with self-reporting is evident in that it relies on every individual properly checking their body temperature in advance and that the calibration can widely differ between people. The latter method of thermal imaging camera also has the issue of calibration (Lee et al., 2015). In order to correctly measure the temperature, a calibrated background needs to be prepared. Another concern with both methods is the cost. Self-reporting asks for every individual to own a thermometer of some sort, and the energy cost, as well as the simple price cost, can easily add up when considering large populations. Thermal imaging, on the other hand, can measure a large number of people simultaneously, albeit at a high initial installation cost (Lee et al., 2015), but also has a not insignificant energy cost. The authors have proposed a novel energy-harvesting wireless body temperature sensor device that has the potential to solve or greatly alleviate these issues.

The proposed device utilizes magnetic phase transition and electromagnetic induction in order to measure temperature in the form of electromotive force (Kansha and Ishizuka, 2019). The primary working principle of the device is the fundamental relationship between material temperature and magnetization. One of the important phenomena for this application is the Magnetocaloric Effect (MCE). MCE is the phenomenon in which the temperature of magnetic material changes in the presence or absence of an externally applied magnetic field. For the sake of clarity, the different types of magnetic fields will be distinguished in three ways throughout

Paper Received: 15 April 2023; Revised: 29 June 2023; Accepted: 21 July 2023
Please cite this article as: Kiyomoto H., Sakai Y., Sato Y., Kansha Y., 2023, Application of Magnetic Phase Transition for a Novel Wireless Sensor Device for Body Temperature, Chemical Engineering Transactions, 103, 193-198 DOI:10.3303/CET23103033

this paper. The applied magnetic field *H* will refer to the field given externally from a permanent magnet in most cases of this research. Magnetization *M* will refer to the field caused by the actual alignment or misalignment of magnetic moments in the magnetic working material itself. Finally, the magnetic induction *B*, otherwise referred to as the magnetic flux density, will be distinguished as what is caused by the combination of the former two. The relationship between these values is defined as follows, where μ_0 is the magnetic permeability of free space.

$$B = \mu_0(H + M) \tag{1}$$

When a magnetic material is put under an applied magnetic field, the magnetic moment within the material begins to align accordingly. As it aligns, the magnetic entropy of the material decreases as a result. When this magnetization is conducted adiabatically, the total entropy within the system must remain constant. The opposite change occurs with regard to the lattice vibration and entropy, causing the temperature to increase. In the case of adiabatic demagnetization, the opposite occurs in that the temperature decreases. This magneto-thermodynamic phenomenon is known as the MCE (Gschneidner et al., 2005).

One of the core applications of MCE has traditionally been magnetic refrigeration, a form of heat pump that has been gaining increasing attention as an alternative method to conventional methods. The magnetic entropy change during MCE is used to cool objects with high efficiency (Kotani et al., 2013) and without the use of possibly harmful chemical refrigerants. Studies up until now have been primarily concerned with increasing the energy efficiency, cooling capacity, and operable temperature range surrounding MCE. For instance, there is constant development on novel magnetocaloric materials that exhibits giant MCE for specific target refrigeration temperatures, such as an DyHoCoNi composite for hydrogen liquification (Zhang et al., 2023) and NiCoMnTi for room temperature application (Guan et al., 2021). Heat pump designs have also been a topic of MCE research, with studies investigating the efficiency and capacity of various designs (Alahmer et al., 2021). However, these studies have only considered refrigeration for MCE application. Instead, this study takes a different approach in utilizing it for an Energy-Harvesting Wireless Temperature Sensor (EHWS) targeted for body temperature. While magnetic refrigeration uses magnetization change to cause a temperature change and transfer heat, the proposed device does the opposite and measures the magnetization change of a material in order to indirectly measure temperature. Here, magnetic properties, specifically in relation to temperature change of a magnetic material, were investigated in order to assess certain criteria regarding the applicability of the proposed body temperature sensor device, such as sensitivity and operation range.

2. Proposed EHWS device

The proposed device, originally proposed by Kansha and Ishizuka (2019), utilizes the change of magnetization due to a temperature change in order to measure temperature. It is also possible to detect the magnetization change in the form of electromotive force through electromagnetic induction with a solenoid. It can be seen that the temperature sensor is also capable of producing electrical energy while operating as a temperature sensor. Since the working material does not need to be in direct contact with the solenoid to cause a change in magnetic induction, the proposed system could also be wireless in the sense that the sensor component, the magnetic working material, and the receiver, the solenoid, can operate without direct contact. It is understood that the proposed system has the potential to operate as an EHWS, as it is a wireless temperature sensor that would also be able to harvest energy out of relatively small temperature changes.

The working principle is based on magnetic phase change and the magnetization change accompanying it. While this form of the sensor was shown by previous studies to be a possibility, whether it is actually apt for a temperature sensor, specifically for body temperature in this case, has not been discussed to date. In order for this magnetic phenomenon to be applied to a functional temperature sensor, several criteria must be cleared. Firstly, a temperature sensor must be sufficiently sensitive and accurate in order to measure the target temperature reliably. In the case of body temperature sensors, it is said that an accuracy of around ± 0.1 °C to ± 0.2 °C should be achieved (Law et al., 2016). Because subject temperature is measured indirectly in the form of a magnetization change, this implies that the magnetization of the chosen working material must be adequately sensitive to temperature change, although amplification treatments in other parts of the sensor device, such as amplifying the induced electromotive force, may aid in adjusting accuracy. Additionally, the magnetic properties, namely the ways in which magnetization changes with temperature, are specific to the working material. This is also an advantage for the proposed EHWS device, as it means that the magnetization is in a way calibrated to each working material, acting as a reference for the temperature sensor. A key temperature is the Curie temperature, or T_C, where a material undergoes a magnetic phase change (Brück, 2007). Hence, T_C is expected to be crucial for the operation of the proposed EHWS as it is where a significant change in magnetization is expected. As a result, the choice of working material is also important for the realization of the EHWS as it determines the operating temperatures and a large part of sensitivity and accuracy of the device.

On the other hand, there are also criteria regarding the non-magnetic aspects of the EHWS. In their initial study, Kansha and Ishizuka (2019) proposed moving the working material within a stationary magnetic field to prompt magnetic phase transition. In such a design, the path and speed at which the material is set to move must be uniform to ensure the only variable affecting magnetization change is the temperature. There may be an optimal path of motion for the material that gives better sensor accuracy. Additionally, the post-induction electromotive force must be outputted in some appropriate form. Whether there must be an amplifier circuit or not or noise removal treatment, as well as other issues concerning the electric side of the device, must also be assessed.

Several criteria must be thoroughly assessed for the realization of the proposed EHWS: an investigation on whether the magnetization-temperature relation is apt for a temperature sensor (i.e., sensitivity, temperature range, etc.), an appropriate magnetic working material for the device based on the first criterion, a suitable electric circuit for the signal output, and the actual design of the temperature device (size/orientation of working material, path/speed of working material motion). While many studies related to magnetic materials conduct basic *M-T* investigations, none have done so with the specific purpose of operation as a temperature sensor, much less a wireless body temperature sensor. Here, the first criterion, that is, an investigation of the magnetic properties, was conducted using Gadolinium (Gd) to assess whether a temperature sensor using magnetization change is appropriate or not. If shown to be possible and suitable, it would signify that it would at least be possible to construct a wireless body temperature sensor by using a Gd working material and a magnetometer probe, albeit without the energy harvesting aspect.

3. Temperature sensor using magnetization

The magnetization of a given magnetic material is determined predominantly by its temperature and the applied field. In an isofield environment, magnetization should serve as an indicator of temperature. The magnetization M of a paramagnet is determined by its magnetic susceptibility χ and applied magnetic field H as in the following equation (Hyodo, 2010).

$$M = \chi \cdot H \tag{2}$$

At temperatures well above T_C and in the paramagnetic region, the magnetic susceptibility can be described by the Curie-Weiss law, shown below,

$$\chi = \frac{C}{T - T_C} \tag{3}$$

where T and T_C are the absolute temperatures and Curie temperature, and C is a constant known as the Curie constant. C is material-specific and has the unit K. This law is less applicable near T_C as the inverse function would diverge (Chikazumi, 2011). It can be seen that the magnetization of a material well in the paramagnetic phase should be in an inverse relationship with temperature and proportional to the applied magnetic field. With that said, this property is strictly specific to the given material. If the chemical composition, or even the structural composition, is altered, the magnetic properties may vary, meaning that it is also important for the proposed temperature sensor device to have a working material with a highly replicable composition and structure in order to ensure sufficiently similar magnetic properties.

4. Method

In order to assess the potential applicability of a magnetization-based temperature sensor, magnetization under a varying temperature was experimentally analyzed using gadolinium (T_C = 292 K). Gd was selected as the subject as it has been extensively studied in the past for its magnetocaloric properties, making it a good reference for this experimental study. The magnetic field was provided using a permanent magnet manufactured by TOWA Industrial Co, LTD, which was reported to have a maximum magnetic field of 1.07 T (Kotani et al., 2014). The magnetic field was measured using a Gauss meter by Lake Shore Cryotronics Inc. with the HMMT-6J04-VF probe (accuracy: ± 0.10 %).

The experimental setup is as illustrated in Figure 1 below. The Gd nugget was first heated or cooled down to a target temperature using a water bath and dry ice, then placed in the stationary position within the permanent magnet corresponding to the applied field strength conditions. The nugget used had a mass of 2,670 mg. The change in magnetization was measured using the Gauss meter probe as the nugget temperature, which was monitored using a type K thermocouple probe by Keyence Corporation, naturally rose to the room temperature.

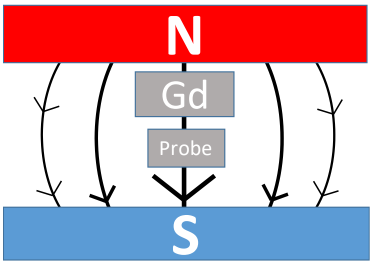

Figure 1: Experimental setup, where Gd represents the Gd nugget, Probe the gauss meter probe, and the arrowed lines the illustration of the applied magnetic field lines within the permanent magnet

Magnetization was measured according to Eq.(1), where B can be considered as the gauss meter reading with the Gd nugget, and $\mu_0 H$ the reading without. While the discussion of the experimental data throughout this paper will refer to the result as the magnetization of the Gd, it should be noted that it is in fact the product of the magnetization and the magnetic permeability of free space. For the purpose of this study, this consideration of magnetization is apt as it retains linearity.

5. Results

The experimental data was used to analyze the magnetic properties of Gd and to assess its potential for a magnetization-based temperature sensor device.

5.1 *M-T* curves

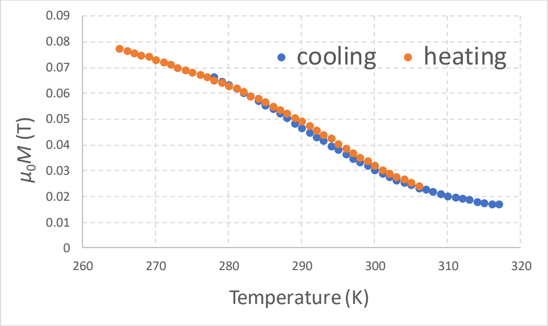

Figure 2: M-T curves of Gd under 1.0 T applied field

By measuring the magnetization as the Gd temperature changes, heating curves and cooling curves were constructed. Shown above in Figure 2 are the magnetization results. It should be noted that the two curves are not to be considered as one converging line but as two individual curves that have similar trends. This is because the two conditions were not collected in a single sampling in which cooling and heating were done cyclically but rather in two separate sampling periods. A cyclically sampled *M-T* curve may be important for the assessment of thermal hysteresis, which plays a large role in magnetic refrigeration. However, for the purpose of a temperature sensor, the trend and relationship between temperature and magnetization are far more important. It can be seen from the results that the magnetic behavior can be characterized in roughly three temperature regions: the low-temperature ferromagnetic region, the phase transition region surrounding T_C, and the high-temperature paramagnetic region. The general trend is that as temperature increases, thermal contribution to the misalignment of magnetic moments causes magnetization to decrease. In the ferro-region, this is a relatively slow process as the Gd still retains high magnetization. However, as it approaches T_C, the material undergoes a phase transition, causing a precipitous drop in magnetization. In the para-region well above T_C, the Gd is known to follow the Curie-Weiss law, as illustrated in Eq.(3). In this phase, the Gd not only possesses lower magnetization in the presence of an applied field but also cannot retain its magnetization in the absence of the field.

5.2 Temperature sensor implications

The different temperature regions on the magnetization curves were individually assessed for the context of a temperature sensor. The ferromagnetic, paramagnetic, and phase transition regions with simple linear regression fitting results are shown in Figure 3 below. It can be seen that within the narrow temperature range of around 10 K, all regions show a high linear correlation, as shown by the R^2 values of 0.99. However, there are clear differences between the phase transition range and the others. First, the width of the temperature ranges in which this linear correlation is held is much greater in the phase transition range. Additionally, while the gradient of the regression is quite low at - 0.0005 TK^{-1} for ferromagnetic and paramagnetic regions, it is significantly greater during phase transition at - 0.0017 TK^{-1}.

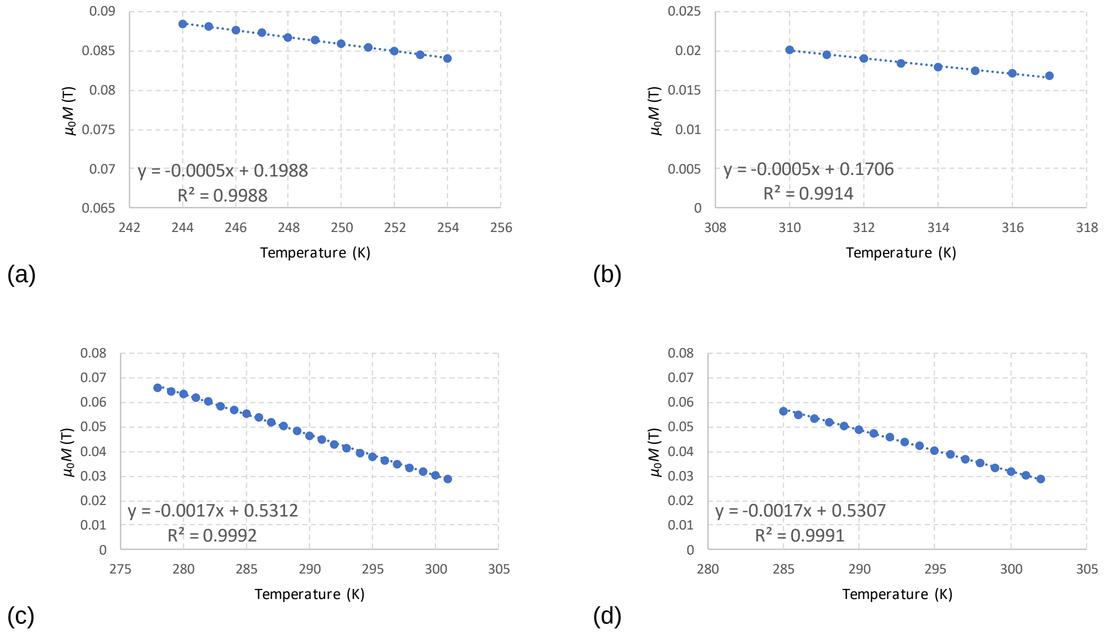

Figure 3: M-T curve under 1.0 T applied field with linear regression fitting at (a) ferromagnetic region, (b) paramagnetic region, (c) phase transition region for cooling condition, and (d) phase transition region for heating condition

For the proposed temperature sensor, the sensitivity of the working material's magnetization with regard to temperature directly translates to the sensitivity and the device performance. As explained previously, the proposed device aims to apply electromagnetic induction in order to measure temperature in the form of electromotive force. As shown in Eq.(4) below, Faraday's law of electromagnetic induction states that the electromotive force induced within a solenoid is a function of the number of coils n and the time derivative of the magnetic flux Φ. In this case, based on the definition of magnetic induction, and Eq.(1), the magnetic flux due to the Gd can be understood as a function of applied field and temperature. As a result, under an isofield condition, the sensitivity of the magnetization with regard to temperature also affects the electromagnetic induction. While it is possible to amplify the electromotive force by increasing the number of coils or through an amplifier circuit, this could cause tradeoffs with signal noise, which again poses concerns regarding the sensor device performance.

$$\varepsilon = -n\frac{d\Phi}{dt} \tag{4}$$

Based on the linear regression analysis, it can be seen that the phase transition region which surrounds the T_C of the material is the most apt region for a magnetization-based temperature sensor. While this may be useful for certain sensor subjects, the typical human body temperature is well beyond this temperature range. Different magnetic materials must be developed for application as a body temperature sensor. Also, it was shown that the phase transition region shows a high *M-T* gradient and wide temperature ranges. This may be contrary to was explained in that magnetic phase transition is not occurring in a first-order fashion at a single temperature point, T_C. This is because the magnetic phase transition of ferromagnetism, especially when measured as bulk magnetization (as in the Gd nugget) and at relatively low magnetic field, behaves as a second-order transition (Gschneidner et al., 2005). A similar magnetic-thermal analysis in a more microscopic scale and significantly higher applied field should exhibit a first-order like phase transition at T_C. However, for the purpose of this research and the proposed application for a temperature sensor, the continuous behavior of the phase transition is beneficial in providing a range of operational temperatures. The two criteria of temperature sensor sensitivity and operational temperature range were assessed based on the magnetic properties of Gd. It was shown that, strictly in terms of magnetization change and within the phase transition region, it is technically possible to use Gd and Gauss meter (with the accuracy of what was used here) for a magnetization-based temperature sensor device. However, Gd was shown not to be a suitable working material for accurately measuring body temperature.

6. Conclusion

In this paper, a magnetic-thermal investigation was conducted using gadolinium to assess the potential of a magnetization-based temperature sensor device. The proposed device utilizes the magnetization change of a magnetic material and Faraday's law of induction to determine the temperature of the subject in the form of electromotive force. The proposed temperature sensor device also has the potential for operation as an energy harvester. An experimental analysis using Gd was conducted to assess the *M-T* relationship and its applicability to a body temperature sensor. The results show that the temperature region near T_C, around 278 K to 302 K, in which the Gd is undergoing a magnetic phase transition, is the most suitable region for operation as a temperature sensor with a linear regression gradient for *M-T* of - 0.0017 TK^{-1}. However, this temperature range is well below the typical human body temperature, and because this magnetization change is specific to Gd, different magnetic materials with a more suitable phase transition temperature range must be developed in the future. This, along with similar investigations on the electric circuit and device side of the criteria, such as the orientation and method of magnetization of the working material, addition of an amplification circuit, and other circuit-side noise reduction methods, would allow for the realization of the proposed energy harvesting wireless body temperature sensor device.

Acknowledgments

This research was supported by Japan Society for the Promotion of Science (21H01868), and Japan Science and Technology Agency (JPMJFR2170).

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